ELSEVIER

CrossMark

Procedia Computer Science

Volume 66, 2015, Pages 730–739

YSC 2015. 4th International Young Scientists Conference on Computational Science

Procedia Computer Science

Improving Visualization Courses in Russian Higher Education in Computational Science and High Performance Computing

Andrey Karsakov, Anna Bilyatdinova and Alexey Bezgodov

ITMO University, Saint Petersburg, Russia

kapc3d@gmail.com, a.bilyatdinova@gmail.com, demiurg@gmail.com

Abstract

In order to keep up with the fast-paced and widespread technologies and applications of visualization, worldwide education community is actively implementing visualization courses in curricula of undergraduate and graduate programs. A study of the state of the art in the teaching visualization in Russian higher education shows the necessity to improve the quality and breadth of knowledge of the visualization courses. In this paper we propose our approach to overcome the national and historical challenges in teaching visualization in Russian STEM higher education on the example of Computational Science and High Performance Computing double degree Master's programs in ITMO University. We offer a smooth transition to the modern relevant syllabus content by presenting two courses' designs with same width but with various depth in knowledge that should to be studied. At the end of the paper we give some discussions about future works in development visualization courses in Russia.

Keywords: Visualization course, Computational science, Higher education

1 Introduction

At the moment, there is no disputes about the importance of visualization in almost all areas of modern life - from entertainment to engineering and science. A daily-growing computing power, all-round computerization, development of Internet of Things and a host of other things lead to an incredible growth of the amounts of collected and processed data that is difficult (or impossible) to understand without a proper visual interpretation [1], [2]. Moreover, visualization and interaction techniques [3] allows us to bridge the gap between scientific society and applied specialists [4] as well as between educators and students [5]. Result of the research in the visualization domain over the last few decades is that the issues of the need to use visualization in education [6], [7] and training visualization skills [8] are non-existent.

Education in Computational Science (CPS) and High Performance Computing (HPC) has a direct bearing on this issues. This is one of the domains that critically needs a good visualization course in

Selection and peer-review under responsibility of the Scientific Programme Committee of YSC 2015

doi:10.1016/j.procs.2015.11.083

program curriculum due to simulations, mathematical models and huge amount of diverse data. The presence of visualization courses in CPS programs differs in each university [9]. They are presented at all levels of education, from undergraduate [10] to graduate school [11]. Inner temporal distribution of courses in master's program also varies from the first to third semester [12]. In some cases, initially such courses are held in two semesters [13], but with the program evolving, the course was reduced to one semester [14]. Approach to setting the priority of visualization course in a curriculum also differs due to the applied specifics. The course may be included both as a core course (sometimes even several core courses [15]) and as an elective course [16], or even may be included as a block or a series of lectures into other courses (e.g. Visual Analytics or Data Analysis).

All examples considered above, as well as many other visualization courses in CPS programs have many common topics and themes, and follow certain guidelines in courses' design as a consequence of a rather broad community and numerous researches in this domain. Already in the late 90s Gitta Domik in cooperation with ACM SIGGRAPH Education Committee closed the question about the need for formal education in visualization [17] and formalized the guidelines for design of the courses in visualization for the community of educators [18]. After a while, along with evolution of visualization courses, Rushmeier et al. singled out that visualization education is not just a subject within computer science and is increasingly relevant to a broadening range of disciplines [19]. So the key question shifted from "Do we need formal education in visualization?" to "How can we support and provide flexible education in visualization?" As training in visualization is a fully interdisciplinary task, the authors also specify the necessity to involve colleagues from other domains to expand the base of resource and educational material by a variety of applications.

On the other hand, visualization domain is not only multidisciplinary in its content, but also appealing to and in demand to a wide range of professionals (business and industry), even to those considerably distant from STEM (Science, Technology, Engineering and Math) domain such as designers and journalists [20]. This tendency was detected by Owen et al. [21], but in terms of growing interest to the courses on visualization among nontechnical students in recent years. Moreover, having reviewed the latest alterations in such courses and identified three distinct areas in visualization (scientific or data visualization, information visualization and visual analytics), his team derived that all three areas share learning objectives and themes that constantly should be covered by educators to keep courses up-to-date.

In Russian higher education and in the ITMO University in particular, educational programs for CPS are considerably younger than at the foreign universities and developing by leaps and bounds over the past few years [22]. Creators of these joint programs set very audacious goals to make master program internationally recognizable and to ensure that graduates stand out from the crowd in the job market worldwide [23]. Therefore, the content of the "Scientific Visualization and Virtual Reality" course should fully meet these goals. For that end, we must overcome a number of challenges due to historical and national peculiarities of Russian higher education evolution that are described in details in next section.

2 Teaching Visualization in Russian Higher Education

2.1 Brief History and Current State of Visualization Courses in Russian Higher Education

Education in Russia has certain local features in the development of teaching visualization. Nowadays STEM higher education and Computational Science in Russia are substantially rooted in the Soviet engineering school. The role of visualization in engineering education before Perestroika was performed by the courses in Descriptive Geometry (DG) (also known as engineering drawing) and a set of National

State Standards (GOSTs), which determine the basic rules and principles of how to draw blueprints, charts, tables of data and so on. This knowledge base was used by each of engineers and scientists to design their results in USSR.

In the 90s, the fall of Soviet Union and accompanying emergence of economic and social problems of the transition period, formed a gap in the development of scientific academic domain [24] and as a consequence in higher education [25]. During this period the world community experienced a stage of an active formation of visualization education [17]. In the middle of 90s of the past century with the situation in Russia and CIS stabilized and growing governmental support of higher education, resistance to occurring changes in education was present at many levels. The younger generation preferred to work in business rather than pursue career in science and education, due to its low reputation at a time. Older generation of academic staff being loyal to teaching as a calling or just reluctant to changes, were accustomed to work with old hard standardized (as in the Soviet era) program [26].

In the late 90s - early 2000s, the subsequent transition to the Bologna system and the creation of new educational standards began to bear fruit. But according to numerous above-mentioned reasons, implementation of these educational initiatives gained a corresponding after-taste. With gradual penetration of computer technologies in STEM education, DG evolved into studying CAD systems almost exclusively in engineering and technological education, but disappeared from IT and science education as not required by educational standards.

Courses on teaching visualization began to emerge in Computer Science (CS) education [27], [28]. Some of them evolved in separate graduate programs designed with the main goal to train highly qualified software engineers/developers/researchers with a focus on Computer Graphics (CG) and related fields. This approach is still relevant in teaching even today and, as a matter of fact, these programs do it great (Hydra renderer (http://goo.gl/p8OaNL) is commercially viable at the global market of solutions for rendering, and it was developed by the graduates of Keldysh Institute of Applied Mathematics [29]). However, this thorough engineering approach is poorly applicable in the case of Computational Science, mainly due to its redundant depth in CG technologies and, as a consequence, a very weak coverage of all other topics of Visualization as a vast multidisciplinary domain.

Likewise, the following fact should not go unnoticed. On the edge of centuries the meaning of the term “Visualization” in the Russian language was somewhat distorted and became synonymous to the “Rendering” term, as a result of the advent and widespread (thanks to the uncontrolled piracy [30]) of consumer’s CG (software to create CG and animation) in the post-Soviet space. Courses in Computer Graphics and Visualization in many universities were refocused to study 3D-editors or highly specialized visualization tools. Unfortunately, without sensible explanation of basic principles and concepts why these steps should be performed at all (even if there are “fundamentals” or “introduction” appear in the name of course). Sad but true, this approach still finds its application [31].

This brings us to another significant challenge reflected in rigid separation between educational components of Technologies and Liberal Arts in visualization. If we look closely at the history [32], visualization inherently brings together exact sciences and humanities. That’s why exclusion of humanitarian components of visualization such as psychology and physiology of visual perception, color encoding and patterns, design and layout, or even free-hand drawing (which can be very useful in science education [33]) from the courses for technical students leads to lopsided study of the subject.

As a result, it turns out that the most of Russian students are constrained to earn a degree in STEM without basic understanding of visualization principles. Every year that gap brings more and more critical consequences for graduate students - from problems with adequate demonstration of their skills and research results to low competitiveness at the labor market. Having overcome these difficulties, educational institutions could put more emphasis on proper “sale” of students in the labor market and significantly reduce the gap between science and industry observed in the Russian Federation and CIS.

Keeping up the pace with foreign leaders in higher education, some of top 20 Russian universities [34] already began to implement courses on visualization into the wide range of educational programs. These emerging courses reflect current trends, full of content and based on modern relevant literature.

Nevertheless, the described phenomenon is of more local character (in terms of application domain) than a common practice, for instance, Master's program "Big Data Systems" in High School of Economics [35].

2.2 Current State of Visualization Education in ITMO University

ITMO University is currently in a transition period from obsolete remnants of purely engineering education to fighting for a competitive role at international market of IT education. In the framework of curricula design, visualization domain is in spotlight due to a great variety of elective courses [36].

Mainly these courses are an integral part of programs in computer graphics and multimedia. These courses are specialized, touch the depths of the matter and with a strong focus on technologies [37], [38]. Even a double-degree program with Lappeenranta University of Technology on Computational Science [39] is devoted to computer graphics, computer vision systems and complex systems of image understanding, thus it is no wonder that there are general courses on visualization. However, this approach and its pros and cons were discussed in Section 2.1. As mentioned in introduction, there are 3 double-degree master's programs in Computational Science with University of Amsterdam at HPC department [40]. It is worth mentioning that our programs have no clear connection with CG. *Scientific Visualization and Virtual Reality* is an elective course and assigned for the 3rd semester.

Initially, this course was designed with a reference to the approaches common for Russian education system focusing on technological component. Our course significantly prevails in thorough study of real-time CG programming above all other aspects of visualization. However, the course being delivered, we had observed both Russian and international educational trends in visualization. Gradually we have introduced different kinds of satellite events to evoke interest to visualization.

3 Satellite Educational Activities and Interim Results

Due to the nature of HPC applications, majority of our master students are not only studying but also working part-time at eScience Research Institute in research groups in real research projects [22]. Distribution of students to research groups takes place at the beginning of the first semester; a priority in the group choice is given to the students. Rather diverse and multi-disciplinary background of incoming students is also taken in consideration.

Already in 2013 intake, an increasing interest in the visualization research group was observed, but at that moment, instructors did not pay enough attention to that fact. Due to this interest at the end of the second semester, it was decided to organize an optional group project using a visualization tool developed in eScience Research Institute [41]. The main goal of this project was to develop and evaluate their creativity and soft skills. Overall results of this project revealed that students were able to present their group works using only a restrictive set of tools in clear, aesthetic and qualitative manner. Students' presentations were assessed not only by expert, but also by peer evaluation. A great positive feedback from participants stimulated our enthusiasm as educators. Participants commented that they are interested in working with high-quality software with a good visual representability, but equally, it would be interesting to learn all aspects of how to create similar software.

We would also like to point out results of the students from 2013 intake. Students that conducted research under the supervision of visualization team leader excelled at the master`s thesis presentation and Thesis Board individually and positively highlighted accessibility, clarity and visibility of their presentations.

Intake of 2014 confirmed the trend of the previous year, with almost half of the intake subscribed into the visualization group. According to an informal inquiry, many students turned out to be not only interested in working on a variety of interesting projects, but also were interested in improving visualization skills. This applied not only to those who wanted to join a visualization team, but also to the students from other groups (research areas).

Due to the increased demand and attention to visualization domain, our team at our own initiative, launched an optional course (outside the program curriculum) on introduction to visualization techniques. Course covered the basics of visualization, computer graphics and the principles of visualization applications development using Fusion framework developed in eScience Research Institute [42]. These activities resulted in unpretentious video games (as one of the telling examples of visualization applications in the absence of clear objectives and datasets) created by solely the students on proposed framework. All students succeeded in one way or another and some even showed remarkable creativity. In addition, as teachers we were able to estimate roughly what each of the students is capable of.

During these activities, some students ceased to attend our optional course for a number of reasons. Modern master students in Russia have a rather vague understanding of visualization, due to the lack of the courses in visualization at the bachelor level and some other factors described in Section 2.1. As a result, after a couple of lessons, some students realized that this was not what they had imagined and decided not to waste their time. The second reason was evidently an optional character of the course. Thus, referring to a serious academic load, other part of the students was forced to abandon the course in favor of the courses in their major. Just 12 most devoted students managed to complete the course, which is more than a third of initial intake (a total amount – 32 [22]). We considered it a major success for this kind of activities.

Curiously, many of the students who finished this course continued to use Fusion framework in their current research activities. In addition, we have received from students' positive feedback in overall proposals and recommendations about how they would like to improve this course, what it lacks and what information is redundant for an introductory course.

With the development and extension of double degree programs, more opportunities for improvement of individual courses have appeared. So, for students of 2014 in the spring semester a set of classes on *Introduction to Data Visualization* through *Big Data* course was held to improve their skills and general level of knowledge. These lectures also deserved a positive feedback from students, and those who took our optional course on visualization in the first fall semester noted that it would be useful to combine these two activities.

Assessing the results of all activities undertaken and of feedback we had received in general, we confirmed the validity of trends identified by Owen et al. [21] for growing popularity of visualization courses for Russian students. It has become a serious impetus for further development of our courses.

At the same time, skills and background Russian students, which should form the basis for the course design, could be viewed at different angles: a) students with good computer science background with little or none basics of visualization; b) students with applied domain background have close to minimum experience in software development.

It is therefore necessary to reduce the entry barrier of CS background and develop not only narrow technical skills. Introduction of interdisciplinary components (basics of visualization as an art) in the educational process for STEM students should better develop students` skills in presenting their research results in a clear and "marketable" form not only during education but also in their future career.

On the basis of all of the above, we conclude that the structure of visualization courses and its place in the curriculum should be revisited both to improve the final quality of graduates and to meet the growing demand for visualization courses. Our team formulated main challenges in improving this visualization course are a) to provide an opportunity to maximize learning outcome for the second-year students and b) to expand the course in depth for students of 2015 enrollment. In the next Section, we describe our approach of a smooth transition from outdated education concepts to the courses that meet modern trends in both teaching visualization and Computational Science and High Performance Computing with a minimal loss in quality of the material being taught.

4 Proposed Approach of a Smooth Transition of Visualization Course to Modern Conditions

4.1 Common Issues

To overcome the challenges pointed in a previous section we have designed two courses with unified and wide coverage of domain, but with different depth of knowledge. According to program curriculum, 68 academic hours (34 classes) are reserved for an elective course, thus for our course design we have chosen a time schedule of 17 weeks with 2 classes per week. Table 1 shows the time distribution of the topics covered by classes (numbers in the table cells show the indices of the weeks in the schedule) in the courses for the second year students and for students from new intake in the first and in the last two columns, respectively.

We have reviewed a wide variety of courses in foreign universities, researches in teaching visualization, current trends in visualization and course design. So the syllabi of our courses were influenced partly by courses at Harvard University [43], Georgia Institute of Technology [44], The University of Paderborn guidelines for visualization curriculum [18], Owen et al. research [21] and by standard textbooks such as *Visualization Analysis and Design* [45], *Interactive Data Visualization: Foundations, Techniques and Applications (2nd Edition)* [46] and *The Functional Art: An introduction to information graphics and visualization* [20].

In our practice, we recommend extra books or chapters to students for further reading and enrichment. For example, *Interactive Data Visualization for the Web* [47], *Data Visualization: Principles and Practice* [48], *Design for Information* [49], *Visual Thinking for Design* [50]. After each lecture, students are also invited to explore a series of research papers related to discussed subjects.

4.2 Syllabi

The vast majority of themes and topics indicated in our syllabi (such as introduction to visualization, perception, task analysis, data processing, interaction techniques and so on) are mostly common for the majority of visualization courses abroad. Hence, we would like to mention only standout features of our course design.

Practical Sections mentioned in Table 1 are supplementary 45 – 90 minutes practical classes. They are intended to teach students necessary technical skills and consist of short presentations, live coding and Q&A time about homework. Design Studios are similar to Practical Sections in structure, but mainly intended to give students skills in designing visualizations with data analysis and free-hand sketching [51] individually or in teams. This approach is a little bit unusual for Russian STEM education, where predominance of "laboratory classes" rules (receive a task in the beginning of the class, accomplish it and get teacher's assessment).

In the middle of the course, we made a small emphasis on liberal arts component of visualization with *Gettin' Deeper in Visualization* classes. Our plans are in discussion of a social value of visualization and involvement of art in current visualization domain at these classes. These are particularly interesting topics on account of advancement of STEM to STEAM (http://goo.gl/Fs3AX9) actively promoted by the Rhode Island School of Design (http://goo.gl/MwlcXf) and ACM SIGGRAPH Education Community (http://goo.gl/HTvZwS).

We would also like to note the reasons why a lot of time is devoted to Fusion framework and Workshops on Fusion (personal projects) in our syllabi. Fusion framework is a multipurpose development environment built on a user-friendly C# programming language. It is actively used in ongoing research projects of eScience Research Institute for visualization purposes [52]. Consequently, the framework itself and its development is one of the areas of interest of our team. As previously mentioned, students at HPC Department almost immediately are involved in real research work. Using Fusion framework as

Fall 15	Topics	Subtopics	Fall 15	Fall 16
1	Introduction	What is Visualization and Why we do it?	1	1
		Brief History & Impact of future technology		
		Introduction to D3	2	
2	User & Tasks	Perception & Cognition	3	2
		Task analysis, abstraction and validation		
3	Data	Examples of complex data sets	4	
		Data types and world being modeled		
		Data processing & Data models		
4	Foundations	Visualization Pipeline		3
		Marks and Channels	5	
5		Mapping Process & Design Principles		
		Design Studio 1		
6	Interaction	Interaction flow and design	6	4
		Human performance and limitations		
		Implementation techniques & Evaluation		
		Practical Section 1	7	
7	Representations	Categorization		
		Computer Graphics		5
		- Techniques		
		- Real-time CG		
		- Advances of GPGPU		
8		Representation techniques	8	6
		- Visualizing Tables		
		- Spatial Data. Geospatial Data. Maps		
		Practical Section 2		
		- Time-Oriented Data & Multivariate Data		7
9		- Hierarchies, Trees, Graphs, and Networks		
		- Text and Documents	9	8
		- Software Visualization		
		Design Studio 2		
10	Gettin' Deeper in Visualization	Communication & Collaboration	10	
		Social visualization		
		Visualization and arts		
		Visual analytics	11	
		Value/benefits of visualization		
11	Advanced HCI	Virtual Reality		9
		Emerging devices and technologies in HCI		10
		Practical Section 3	12	
12	Visualization Tools	Common vis software and toolkits		11
13		Advanced real-time graphics & Game Engines		12
		Fusion framework		
14 -17		*Workshops on Fusion (personal projects)*		13-17

Table 1: Visualization course syllabus

an educational component, we solve three problems simultaneously. Firstly, through education process students are involved in research projects faster. Secondly, we simplify students' acquisition of basic CG programming skills. Thirdly, in addition to D3.js as a solution for interactive web visualization, students receive a flexible tool to implement their own ideas as a standalone application.

4.3 Difference between 1- and 2-semester syllabi

The course for the second year students, that have received just some pieces of basic knowledge in visualization during the first year, covers all the topics by concentration of the education material and reduction of its depth and practical training. The practical part includes mastering the basics of D3.js at the first half of the semester, and more in-depth study of CG and creation of visualization applications using Fusion framework, C # and DirectX in the semester's second half.

The course for the new students' intake is divided into 2 semesters. The first semester (Fall 2015), as in 2014, is completely optional and goes very briefly in technical issues, but puts more emphasis on the basics of visualization and design concepts. All the technical details are covered by the lectures and practice in D3.js, as a simple widespread tool for visualization on the web. To avoid conflicts in students' schedule, this course is reduced to 12 weeks (instead of 17 standard weeks) and contains only two Design Studios and two Practical Sections. The second semester's course intersects with the first one on many topics, but more targeted at enhancing technical and applied skills in visualization. It contains only one *Design Studio*, but three *Practical Sections* and 5-week block of *Workshops on Fusion framework*. Both courses could be taken independently and supplement each other. Thus logically, we can identify these courses as a *Visualization Basics & Design* and *Applied Visualization & Computer Graphics*.

Since the topics' are overlapping in the courses for 1st and 3rd semesters, it is possible to give more freedom of choice for students. For example, there is no need to finish the first course to get the next one in 3rd semester. And vice versa, if a student passes the course of the first semester, but he or she might not choose this course as an elective in the third semester. In any case, students will already have basic knowledge and skills in visualization (albeit with lesser depth in technical terms). For those who prefer to pass both courses, overlapping topics will be reviewed further and in more details, since the courses' content is complementary rather than repetitive.

5 Conclusions and Future Work

In this article, we propose an approach to bridge the gap between a current state of visualization courses in Russian higher education and modern worldwide conditions and ongoing trends in teaching visualization. We offer two courses to cover the transition from old to new approaches in one year. Syllabi were influenced by existing courses at the leading universities, recommendations for curriculum design in visualization of ACM SIGGRAPH Education Committee and recent textbooks. In addition, courses were designed with an eye on the particularities of teaching process and research domains of HPC Department and eScience Research Institute. We hope that the proposed approach will bring our course in line with contemporary educational standards with a greater efficiency for our students, even those who are already studying at master programs.

The infancy of the department and visualization courses complicate quantitative assessment of the quality of educational activities. Validation of expected outcomes is to be obtained by testing our suppositions in 2015 and 2016. Having studied the effectiveness and popularity of both courses, we plan to discuss with our stakeholders to what extent it is relevant to extend this course to 2 semesters, instead of generally applicable 'one semester' approach.

Acknowledgements

This paper is supported by Russian Scientific Foundation, grant #14-21-00137 "Supercomputer simulation of critical phenomena in complex social systems".

References

[1] A. V. Pandey, A. Manivannan, O. Nov, M. Satterthwaite, and E. Bertini, "The Persuasive Power of Data Visualization," *IEEE Trans. Vis. Comput. Graph.*, vol. 20, no. 12, pp. 2211–2220, Dec. 2014.

[2] M. Gleicher, D. Albers, R. Walker, I. Jusufi, C. D. Hansen, and J. C. Roberts, "Visual comparison for information visualization," *Inf. Vis.*, vol. 10, no. 4, pp. 289–309, 2011.

[3] J. S. Yi, Y. ah Kang, J. T. Stasko, and J. A. Jacko, "Toward a Deeper Understanding of the Role of Interaction in Information Visualization," *IEEE Trans. Vis. Comput. Graph.*, vol. 13, no. 6, 2007.

[4] M. Berger and V. Cristie, "CFD post - processing in Unity3D," *Procedia - Procedia Comput. Sci.*, vol. 51, pp. 2913–2922, 2015.

[5] K. Ryabinin and S. Chuprina, "Using Scientific Visualization Tools to Bridge the Talent Gap," *Procedia Comput. Sci.*, vol. 51, pp. 1734–1741, 2015.

[6] K. L. Vavra, V. Janjic-Watrich, K. Loerke, L. M. Phillips, S. P. Norris, and J. Macnab, "Visualization in science education," *Ain Shams Eng. J.*, vol. 41, no. 1, pp. 22–30, 2005.

[7] John K. Gilbert (ed.), *Visualization in Science Education*, vol. 41, no. 1. 2005.

[8] D. F. Ali and M. S. Nordin, "Visualization Skills among Universiti Teknologi Malaysia Student," vol. 2, no. 4, pp. 371–373, 2012.

[9] Society for Industrial and Applied Mathematics, "Graduate Programs in Computational Science," 2015. [Online]. Available: http://www.siam.org/students/resources/cse_programs.php.

[10] L. J. Little, "The computational science major at SUNY Brockport," *Futur. Gener. Comput. Syst.*, vol. 19, no. 8, pp. 1285–1292, 2003.

[11] S. Holmgren and A. Ynnerman, "The Swedish National Graduate School in Scientific Computing (NGSSC)," *Futur. Gener. Comput. Syst.*, vol. 19, no. 8, pp. 1275–1283, 2003.

[12] USI Università della Svizzera italiana, "The master in Computational Science." [Online]. Available: http://www.mcs.usi.ch/index.htm. [Accessed: 09-Aug-2015].

[13] H.-J. Bungartz, "Computational science and engineering: a new master's program at the Technische Universität München," *Futur. Gener. Comput. Syst.*, vol. 19, no. 8, pp. 1267–1274, 2003.

[14] Technische Universität München, "Computational Science and Engineering (M.Sc.)." [Online]. Available: https://www.in.tum.de/fuer-studieninteressierte/master-studiengaenge/computational-science-and-engineering.html. [Accessed: 11-Jun-2015].

[15] North Carolina A&T State University, "Master of Science Degree in Computational Science and Engineering." [Online]. Available: http://www.ncat.edu/academics/schools-colleges1/coe/cse/masters-program/index.html. [Accessed: 03-Aug-2015].

[16] The University of Amsterdam (UvA), "MSc Computational Science." [Online]. Available: http://www.uva.nl/en/education/master-s/master-s-programmes/item/computational-science.html. [Accessed: 11-Jun-2015].

[17] G. Domik, "Do we need formal education in visualization?," *IEEE Comput. Graph. Appl.*, vol. 20, no. 4, 2000.

[18] The University of Paderborn, "Guidelines and teaching materials for visualization and graphics curricula and courses," 2015. [Online]. Available: http://www.uni-paderborn.de/cs/vis.

[19] H. Rushmeier, J. Dykes, J. Dill, and P. Yoon, "Revisiting the need for formal education in visualization," *IEEE Comput. Graph. Appl.*, vol. 27, no. 6, pp. 12–16, 2007.

[20] A. Cairo, *The Functional Art: An introduction to information graphics and visualization*. Berkeley: New Riders, 2013.

[21] G. S. Owen, G. Domik, D. S. Ebert, J. Kohlhammer, H. Rushmeier, B. S. Santos, and D. Weiskopf, "How visualization courses have changed over the past 10 years," *IEEE Comput. Graph. Appl.*, vol. 33, no. 4, pp. 14–19, 2013.

[22] V. V. Krzhizhanovskaya, A. V. Dukhanov, A. Bilyatdinova, A. V. Boukhanovsky, and P. M. A. Sloot, "Russian-Dutch double-degree master's programme in computational science in the age of global education," *J. Comput. Sci.*, vol. 10, pp.288-298, 2015. http://dx.doi.org/10.1016/j.jocs.2015.05.001

[23] A. V. Dukhanov, V. V. Krzhizhanovskaya, A. Bilyatdinova, A. V. Boukhanovsky, and P. M. A. Sloot, "Double-degree Master's Program in Computational Science: Experiences of ITMO University and University of Amsterdam," *Procedia Comput. Sci.*, vol. 29, pp. 1433–1445, 2014.

[24] A. Smolentseva, "Challenges to the Russian academic profession," *High. Educ.*, vol. 45, no. 4, pp. 391–424, 2003.

[25] M. S. Johnson, "Historical legacies of soviet higher education and the transformation of higher education systems in post-Soviet Russia and Eurasia," in *The Worldwide Transformation Of Higher Education (International Perspectives On Education And Society)*, vol. 9, 2008, pp. 159–176.

[26] J. Elliott and J. Tudge, "The impact of the west on post-Soviet Russian education: change and resistance to change," *Comp. Educ.*, vol. 43, no. 1, pp. 93–112, Feb. 2007.

[27] Russian Educational portal, "State Education Standard for Master's Program in Mathematics and Computer Science," 2000. [Online]. Available: http://www.edu.ru/db/portal/spe/os_zip/511800_2000.html.

[28] Russian Educational portal, "Curriculum for BSc in Mathematics and Computer Science," 2000. [Online]. Available: http://www.edu.ru/db/portal/spe/plan_zip/511800bp.html.

[29] Keldysh Institute of Applied Mathematics, "Home page," 2015. [Online]. Available: http://keldysh.ru/index.en.shtml.

[30] a M. Collisson, "The end of software piracy in Eastern Europe? a positive outlook with international help," *Fordham Intellect. Prop. Media Entertain. Law J.*, vol. 14, no. 4, 2004.

[31] E. Kryuchkov, V. Alekseev, S. Ermakov, N. Geraskin, A. Pasko, V. Pilyugin, E. Malikova, E. Kulikov, A. Falin, and A. Peshekhonov, "The Development and Testing Of Distance Educational Course 'Fundamentals of Scientific Visualization' Experience at NRNU 'MEPHI' and Its Branch Establishments," *Sci. Vis.*, vol. 1, no. 6, pp. 20–30, 2014.

[32] M. Friendly, C. Chen, W. Härdle, and A. Unwin, "A Brief History of Data Visualization," *Handb. Data Vis.*, pp. 15–56, 2008.

[33] S. Ainsworth, V. Prain, and R. Tytler, "Science education. Drawing to learn in science.," *Science*, vol. 333, no. 6046, pp. 1096–1097, 2011.

[34] "National university rankings (in russian)." [Online]. Available: http://www.univer-rating.ru/.

[35] Higher School of Economics, "Master's programme «Big Data Systems»," 2015. [Online]. Available: http://www.hse.ru/en/ma/bigdata.

[36] ITMO University, "MSc Applied Informatics in the Information Domain." [Online]. Available: http://edu.ifmo.ru/ru/subspec/2185/prikladnaya_informatika_v_informacionnoy_sfere.htm.

[37] ITMO University, "MSc Computer Visualization Technologies." [Online]. Available: http://edu.ifmo.ru/ru/subspec/2296/tehnologii_kompyuternoy_vizualizacii.htm.

[38] Keldysh Institute of Applied Mathematics & ITMO University, "Visualization Technologies Joint Departmant." [Online]. Available: http://www.keldysh.ru/kur/cgraph/IPM_keldisha_Ran.htm.

[39] ITMO University, "MSc Computational Science." [Online]. Available: http://edu.ifmo.ru/ru/subspec/2491/vychislitelnaya_nauka.htm.

[40] A. Bilyatdinova, A. Dukhanov, K. Bochenina, A. V Boukhanovsky, V. V Krzhizhanovskaya, and P. M. A. Sloot, "Dutch-Russian double degree master's program curricula in computational science and high performance computing," in *2014 IEEE Frontiers in Education Conference (FIE) Proceedings*, 2014, pp. 1–8.

[41] A. Karsakov, A. Bilyatdinova, A. G. Hoekstra, and A. G. Hoekstra, "3D virtual environment for project-based learning," in *2014 IEEE 8th International Conference on Application of Information and Communication Technologies (AICT)*, 2014, pp. 1–5.

[42] A. Bezgodov, A. Karsakov, A. Zagarskikh, and V. Karbovskii, "The Framework for Rapid Graphics Application Development : The Multi - scale Problem Visualization."

[43] Harvard University, "CS-171 - Visualization." [Online]. Available: http://www.cs171.org/2015/.

[44] Georgia Tech, "CS 7450 - Information Visualization Course." [Online]. Available: http://www.cc.gatech.edu/~stasko/7450/index.html.

[45] T. Munzner, *Visualization Analysis & Design*. Boca Raton: CRC Press, 2104.

[46] M. Ward, G. Grinstein, and D. Keim, *Interactive Data Visualization. Foundations, Techniques, and Applications*, Seconв Edi. Boca Raton: CRC Press, 2015.

[47] S. Murray, *Interactive Data Visualization for the Web*. Sebastopol, CA: O'Reilly Media, Inc., 2013.

[48] Alexandru C. Telea, *Data Visualization: Principles and Practice*, Second Edi. Boca Raton: CRC Press, 2015.

[49] I. Meirelles, *Design for Information*. Beverly: Rockport Publishers, 2013.

[50] C. Ware, *Visual Thinking For Design*. Morgan Kaufmann, 2008.

[51] P. a Mueller and D. M. Oppenheimer, "The Pen Is Mightier Than the Keyboard: Advantages of Longhand Over Laptop Note Taking.," *Psychol. Sci.*, vol. 25, no. 6, pp. 1159–1168, 2014.

[52] A. Bezgodov and D. Esin, "Complex Network Modeling for Maritime Search and Rescue Operations," *Procedia Comput. Sci.*, vol. 29, pp. 2325–2335, 2014.